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European Patent Office
Office européen des brevets

⑪ Publication number:

0 059 549
A2

⑫

EUROPEAN PATENT APPLICATION

⑬ Application number: 82300766.1

⑮ Int. Cl.³: B 22 D 27/04

⑭ Date of filing: 16.02.82

⑩ Priority: 02.03.81 US 239640

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⑭ Date of publication of application:
08.09.82 Bulletin 82/36

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⑬ Designated Contracting States:
BE CH DE FR GB IT LI SE

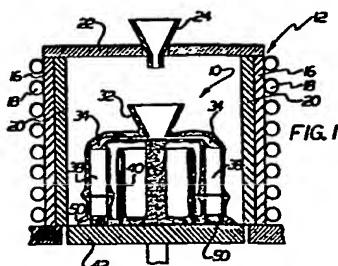
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EP 0 059 549 A2

⑭ An improved method of casting a directionally solidified metal article, such as an airfoil, includes the steps of providing a directionally solidified starter element which is formed of a plurality of elongated metal crystals. In one specific preferred embodiment, each of the elongated metal crystals of the starter element is formed of a plurality of cubic unit cells having sides extending at an acute angle to the longitudinal axis of the crystal such that each cell is advantageously oriented with its [111] direction extending substantially parallel to the longitudinal axis of the elongated crystal. When an article is to be cast, the starter element is positioned at the lower end of a mold cavity and is exposed to a chill. Molten metal is poured into the mold cavity and is solidified. As this occurs, a cast article is formed of elongated crystals having longitudinal axes extending parallel to the longitudinal axes of the crystals in the starter element. Each of the elongated crystals in the cast article is formed of a plurality of cubic unit cells. The sides of the unit cells of the elongated crystals in the cast article have the same orientation as the sides of the unit cells in the elongated crystals of the starter element.



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METHOD OF CASTING AN ARTICLE

Background of the Invention

The present invention relates to a method of casting an article and more specifically to a method of casting a metal article formed of a plurality of elongated crystals having a desired orientation.

The concept of casting an article, such as a turbine blade, with elongated crystals having a [001] direction parallel to the longitudinal axis of the article is disclosed in U.S. Patent No. 3,485,291. The method disclosed in this patent is characterized by initial solidification of the molten metal occurring in a competitive growth zone adjacent to a chill with the longitudinal direction of the article's mold cavity being aligned perpendicular to the chill surface.

This competitive growth zone occurs because when a face-centered cubic metal is cast against a chill, the

initial crystals which are formed will not all have the desired [001] orientation, but rather will be substantially randomly aligned. Since solidifying dendrites in the molten metal grow most favorably in the [001] direction, as solidification proceeds from the chill, those dendrites having an [001] orientation perpendicular to the chill will grow preferentially along the longitudinal axis of the article. Eventually, the preferred dendrites will emerge from the competitive growth zone and result in a series of columnar grains or crystals having a [001] direction oriented in the growth direction. The function of the growth zone from which the preferred or [001] aligned columnar grains emerge is to eliminate from the cast article crystals or grains having an off axis orientation.

After casting, the growth zone is cut off the article and is either discarded or reused to make a new lot of melt stock or so-called master metal, for subsequent casting. The growth zone contributes to casting costs through the use of additional metal, wax material used in producing the pattern for mold making, and additional ceramic material for the mold.

Although the [001] direction of crystallographic orientation which results from directional solidification in the manner disclosed in the aforementioned patents has certain desirable characteristics, such as improved

thermal fatigue resistance, it is well known that other crystallographic directions of orientation can yield higher creep strength and Young's modulus values. For certain applications, higher creep strength and Young's modulus values can be important. However, the obtaining of the crystallographic directions of orientation which yield the higher strength and Young's modulus values cannot be done with conventional directional solidification techniques.

In the past, crystal orientation during the casting of a single crystal article has been controlled through the use of seeds or solid pieces of single crystal material. During casting, metal solidification proceeds from the single crystal seed and causes propagation of a single crystal in an entire casting cavity. Control of the seed temperature and suitable means of cooling the molds are needed to achieve the desired effect in a manner which is further described in U.S. Patent Nos. 1,793,672; 3,139,653; 3,759,310; 3,857,436; and 4,015,657. However, the methods disclosed in these patents have used single crystal seeds to cause the formation of single crystal articles rather than directionally solidified articles having a plurality of elongated crystals with the desired crystallographic orientation.

In an effort to obtain an article having an elongated crystal structure with oriented grains or crystals,

British Patent No. 870,213 teaches the use of a seed slab or starter in the manufacture of ingots having preferred crystallographic properties. The seed slab or starter element has elongated grains oriented so that the (100) crystallographic planes, which correspond to the sides of body-centered unit cells, are substantially perpendicular to the longitudinal axes of elongated grains or crystals of the seed slab. The other sides of the unit cells, that is the sides which extended parallel to the longitudinal axes of the grains or crystals, are randomly oriented and are only occasionally parallel to similar crystal planes in other elongated grains or crystals.

During a casting operation, the seed slab or starter element of the British patent is placed at the bottom of a mold with the longitudinal axes of the crystals extending horizontally, that is perpendicular to the longitudinal axis of the mold. Molten metal is then poured into the mold cavity against the seed slab. The resulting directionally solidified article is formed of elongated crystals or grains having unit cells oriented so as to have a pair of side surfaces extending perpendicular to the longitudinal axes of the crystals or grains and other side surfaces extending parallel to the longitudinal axis of the crystals or grains. The crystallographic orientation along the longitudinal axis is [001], the same as produced through directional solidification in the

making of aforementioned gas turbine articles by competitive crystal growth from a chill surface. Hence, this art does not teach how directions other than [001] could be achieved along the longitudinal axis of the article, cast perpendicular to the chill surface, in order to obtain desired changes in strength or Young's modulus.

Brief Summary of the Present Invention

The present invention utilizes a directionally solidified seed or starter element having elongated crystals or grains. The starter element or seed is oriented in a mold with the longitudinal axes of the crystals in the starter element extending parallel to the preferred direction of grain growth in the mold cavity. This results in the initiation or formation of elongated metal crystals or grains in the mold cavity at the starter element with the longitudinal axes of these grains extending parallel to the longitudinal axes of the elongated metal crystals in the starter element.

By having the elongated crystals in the seed or starter element oriented with a longitudinal axis extending parallel to the direction of grain or crystal growth in the mold cavity, molten metal which is poured into the mold cavity comes into contact with the ends of the longitudinally extending grains or crystals in the starter element. This results in the nucleation of a

multiplicity of crystals or grains having the same orientation as the grains or crystals in the starter element. The nucleation of directionally oriented crystals at the starter element eliminates the competitive growth zone which characterizes most prior directional solidification casting processes.

The longitudinally extending crystals or grains which are nucleated at the ends of the grains in the starter element have unit cells which are disposed in the same orientation as the unit cells of the starter element. By providing a starter element having elongated grains or crystals with unit cells having their side surfaces skewed or extending at an acute angle to the longitudinal axes of the crystals or grains of the starter element, longitudinally extending crystals or grains with unit cells having a similar orientation will be formed in the cast article. It is preferred to orient the unit cells in the starter element in various preselected longitudinal directions to effect the solidification of a cast article having an elongated crystal structure with the unit cells oriented in the same direction. The choice of orientation depends on the specific performance characteristics desired in the article.

As an example of how change in crystal direction can be used to change Young's modulus in the case of a nickel-base superalloy, a casting directionally solidified with

elongated crystals or grains having a [001] direction parallel to the longitudinal axis of the crystals will have an ambient temperature Young's modulus of approximately 18,000,000 pounds per square inch. The same nickel-base superalloy casting would have an ambient temperature Young's modulus in a direction along the casting axis of about 44,000,000 pounds per square inch if the longitudinal orientation of elongated crystals were to lie in the [111] direction. Although the method of the present invention can be used in casting many different types of products, the method is advantageously used to cast airfoils with the elongated crystals or grains having longitudinal axes extending substantially parallel to a longitudinal direction of the airfoil.

Accordingly, it is an object of this invention to provide a new and improved method of casting a directionally solidified article by using a starter element having elongated crystals with longitudinal axes which extend substantially parallel to the longitudinal axes of elongated crystals or grains formed in the cast article.

Another object of this invention is to provide a new and improved method of casting an article, such as an airfoil, wherein unit cells in elongated crystals of the cast article have sides which extend at acute angles relative to the longitudinal axes of the crystals.

Another object of this invention is to provide a new and improved method as set forth in the immediately preceding object and wherein the unit cells of the elongated crystals in the cast article are oriented with their [111] directions extending substantially parallel to the longitudinal axes of the crystals.

Brief Description of the Drawings

The foregoing and other objects and features of the present invention will become more apparent upon a consideration of the following description taken in connection with the accompanying drawings wherein:

Fig. 1 is a schematic illustration depicting the manner in which a mold is supported on a chill with starter elements exposed to the chill and to mold cavities prior to pouring of molten metal into the mold;

Fig. 2 is an enlarged fragmentary sectional view illustrating the relationship between a starter element, a mold cavity, and chill of Fig. 1;

Fig. 3 is an enlarged, somewhat schematicized, illustration of the starter element of Fig. 2;

Fig. 4 is an illustration of an airfoil cast with the starter element of Fig. 3 and schematically illustrating the orientation of a unit cell of an elongated grain or crystal in the airfoil; and

Fig. 5 is an enlarged schematic illustration further illustrating the orientation of a unit cell of one of the

elongated grains or crystals of the airfoil of Fig. 4, the structure of the unit cell being simplified in Fig. 5 for purposes of clarity of illustration.

Description of One Specific
Preferred Embodiment of the Invention

A mold 10 (Fig. 1) is preheated in a known furnace assembly 12 prior to pouring of molten metal into the mold. The known furnace assembly 12 is provided with a refractory outer wall 16 which is surrounded by an induction heating coil 18. A graphite susceptor wall 20 is enclosed by the outer wall 16 and is heated by the induction effect of the coil 18. The furnace assembly 12 has a top plate 22 with an opening which may be provided with a funnel 24 through which molten metal is poured into the mold 10. It is contemplated that the entire furnace assembly 12 will be disposed within a vacuum furnace.

The mold 10 has a pouring basin 32 through which molten metal enters a plurality of runners or passages 34 which are connected with a plurality of mold cavities 38 which are disposed in a circular array around the pouring basin 32. A cylindrical heat shield 40 may be provided on the inside of the circular array of mold cavities 38.

The mold 10 is disposed on a copper chill plate 42. The chill plate 42 promotes the directional solidification of molten metal in the mold cavities to provide a casting having a columnar grain structure with a grain orientation

extending generally parallel to the longitudinal central axes (vertical axes) of the mold cavities 38. It should be noted that although the furnace 12 and mold 10 could have many different constructions, they have the same general construction as the furnace and mold disclosed in U.S. Patent No. 3,680,625.

A starter element 50 (see Fig. 2) is positioned in the lower end portion of the mold cavity 38. The cylindrical starter element 50 is exposed both to the chill 42 and to the mold cavity 38. Thus, a lower or bottom side surface 54 of the starter element 50 is disposed in abutting engagement with an upper or top side surface 56 of the chill 42. The opposite side surface 58 of the starter element 50 is directly exposed to the mold cavity 38.

When molten metal is poured into the funnel 24 and basin 32 to the runners 34 and mold cavity 38, the molten metal flows downwardly against the upper side surface 58 of the starter element 50. Due to the rapid conduction of heat from the starter element 50 to the chill 42, solidification of the molten metal in the mold cavity 38 is initiated at the upper side surface 58 of the starter element 50. As solidification of the molten metal proceeds upwardly in the mold cavity 38, the chill 42 and mold 10 are advantageously lowered to withdraw the mold from the furnace 12 in a known manner.

In accordance with a feature of the present invention, the starter element 50 is formed of a plurality of elongated metal crystals or grains 62 (see Fig. 3) having longitudinal axes which are substantially perpendicular to the opposite side surfaces 54 and 58 of the starter element. The large majority of the grains 62 extend completely through the starter element 50.

The elongated grains 62 have one transverse end disposed in the circular side surface 54 and the opposite transverse end disposed in the circular side surface 58. A few of the longitudinally extending grains 62 may terminate between the two side surfaces 54 and 58. However, all of the grains which end at the side surface 58 have an opposite end at the side surface 54. The elongated grains or crystals 62 have longitudinal axes which extend perpendicular to the side surfaces 54 and 58 and which are disposed in a parallel relationship with a longitudinal central axis 66 (Fig. 2) of the mold cavity 38.

Since the elongated crystals 62 (Fig. 3) have ends disposed in the upper surface 58 of the starter element 50, each of the starter element crystals can effect nucleation of a corresponding longitudinally extending crystal or grain in the molten metal in the mold cavity 38 upon initiation of solidification of the molten metal. This results in the molten metal in the cavity 38

solidifying in a multiplicity of longitudinally extending crystals or grains having their origin at the surface 58 of the starter element 50 and extending parallel to a longitudinal central axis 66 of the mold cavity 38. The elongated crystals which are solidified in the mold cavity 38 have longitudinal axes which extend parallel to the mold axis 66 (Fig. 2) and the longitudinal axes of the grains 62 in the starter element 50. Due to nucleation of the grains in the cast product in the desired orientation at the end surface 58 of the starter element, the competitive growth zone which characterizes many known directional solidification processes where the desired longitudinal direction is [001] can be eliminated.

In the event it is desired to provide the cast article being formed in the mold cavity 38 with a fine grained structure, the starter element 50 has a fine grain structure so that an array of closely packed and relatively small crystal end portions are provided in the surface 58. This results in the formation of a corresponding number of longitudinally extending crystals or grains in the mold cavity 38. Since these grains nucleate at the end surface 58 of the starter element 50, the molten metal solidifies in the mold cavity 38 with a fine grained structure extending substantially throughout the entire length of the mold cavity and with the grains or elongated crystals extending parallel to the axis 66.

Although it is contemplated that the mold 10 could be constructed with the cavities 38 to form different types of articles, the mold 10 is advantageously used to form a directionally solidified airfoil 70 (see Fig. 4). The airfoil 70 has a leading edge portion 74 and a trailing edge portion 76 which extend between a root end portion 78 and a tip end portion 80 of the airfoil. It should be understood that the configuration of the airfoil 70 has been indicated schematically in Fig. 4 and is merely representative of many known airfoil configurations.

When the airfoil 70 is to be cast, molten metal is poured into the mold cavity 38. Although many different types of metal could be utilized, it is contemplated that the molten metal may be a nickel-base superalloy. When the molten metal engages the upper side surface 58 of the starter element 50, elongated columnar crystals or grains 86 (see Fig. 4) are nucleated at the end surfaces of the elongated crystals or grains 62 in the starter element 50. This results in the airfoil 70 having a multi-grained elongated crystal structure which corresponds to the multi-grained elongated crystal structure of the starter element 50.

The elongated grains or crystals 86 in the directionally solidified airfoil 70 have longitudinal axes which extend parallel to the longitudinal axes of the grains 62 in the starter element 50 and to a longitudinal

central axis 88 of the airfoil 70 (see Fig. 4). Although a few of the grains or crystals 86 which are nucleated at the upper face 58 of the starter element 50 may terminate part way through the airfoil 70, the vast majority of the grains 86 extend completely through the airfoil 70 from the root end 78 to the tip end 80 of the airfoil. This results in the airfoil 70 having a multi-grained structure throughout its axial length. Although the airfoil 70 may have a leading edge 74 with a twisted and/or bowed configuration, the elongated crystals 86 extend substantially parallel to the leading edge 74 of the airfoil 70 to enhance the operating characteristics of the airfoil 70 in a known manner.

In accordance with another feature of the present invention, each of the elongated crystals or grains 86 in the airfoil 70 is formed of a plurality of cubic unit cells 94 (Figs. 4 and 5) having the same orientation relative to the longitudinal axis of the crystal. In addition, the unit cells 94 in each elongated crystal 86 have the same longitudinal orientation relative to the unit cells in adjacent crystals. Thus, adjacent longitudinally extending crystals 86 have unit cells which have the same longitudinal orientation relative to the longitudinal central axis 88 of the airfoil 70.

The unit cell, the fundamental building block of the crystal, has an atomic arrangement which, when repeated in three dimensions, gives the total structure of the crystal. The configuration of the unit cell will vary depending upon the material from which the crystal is formed. For the nickel-base superalloy forming the airfoil 70, the unit cell 94 has a face-centered cubic configuration which consists of an atom at each cube corner and one at the center of each face, as depicted in Fig. 4. The orientations within each unit cell is specified in terms of its coordinates relative to orthogonal X, Y and Z axes. When specifying directions in a crystal the notation [XYZ] is used to indicate the direction of a line from the origin to a point the coordinates are X, Y and Z. By custom, brackets are utilized and fractional coordinates are avoided.

Thus, a direction along one of the edges of the cubic cell would also be parallel to one of the three axes and would be denoted as [100], [100], [010], [010], [001], or [001]. In each case, the minus notation above the numeral denotes a negative direction from the origin. Each of these directions is said to be equivalent and of the <100> family. Crystals whose longitudinal axes are vertically aligned and which one of the unit cell axes is also vertically aligned are said to have a [001] orientation, reflecting the convention of denoting the vertical axis as

z. The spatial position of the unit cell may be simply visualized as that of a cube lying flat on one of its faces with the longitudinal central axis 88 being perpendicular to the horizontal plane on which the cube rests.

An extreme form of unit cell orientation occurs in a direction joining the diagonally opposite corners of the cube. This may be visualized as a cube so positioned that one corner makes point contact with a horizontal surface and the other, diagonally opposite, corner falls on a line that both joins the two corners and is perpendicular to the supporting horizontal surface. There are several such equivalent directions in a cubic unit cell, all part of the $\langle 111 \rangle$ family. A crystal in which a direction of this family is parallel to the longitudinal central axis 88 is said to have a [111] orientation. Intermediate between these two extreme orientations of [001] and [111], numerous others are possible. The notation accorded these is well known in the field of crystallography and is not essential to delineating the features of this invention.

Turbine engine blades and vanes produced by the process of directional solidification wherein metal is solidified in contact with a horizontally disposed copper chill typically involve the use of nickel-base superalloys having a face-centered cubic crystall structure. The resulting orientation of elongated crystals in this

process is [001]. The side surfaces or faces of the unit cells lie either perpendicular or parallel to the longitudinal central axis 88 of the airfoil 70. This orientation is recognized as superior from the standpoint of thermal fatigue resistance. However, other orientations, particularly the [111], offer the possibility of greatly improved Young's modulus without sacrifice in creep strength. Such a combination of properties may be attractive in applications where particular vibrational and high temperature strength characteristics are desired and thermal fatigue resistance is not a pacing concern.

In accordance with a feature of the present invention, the airfoil 70 is cast with each cubic unit cell 94 in the same orientation with respect to the longitudinal axis 88 and with each side surface of a unit cell extending at an acute angle relative to the longitudinal axis of the crystals 86. In one extreme case, this results in a cube diagonal corner to corner orientation of the unit cells denoted above as [111]. Thus, each of the side surfaces of the unit cells 94 extends at an acute angle to the longitudinal axes of the crystals 86 and corresponding longitudinal central axis 88 of the airfoil 70. Although the side surfaces of the unit cells 94 are skewed relative to the longitudinal axes, each cell within an individual crystal has the same orientation.

The skewed relationship of the side surfaces of the unit cell 94 relative to the central axis of a crystal 86 has been illustrated schematically in Fig. 4. Thus, the face centered cubic unit cell 94 has side surfaces 96, 98 and 100 all of which extend at acute angles relative to the longitudinal central axis of the crystal 86. Although only three of the six side surfaces of the cubic cell 94 have been identified in Fig. 4, it should be understood that the other three side surfaces of the cubic cell also extend at acute angles to the longitudinal axis of the crystal 86.

Although the unit cells 94 of the crystals 86 could be oriented with the side surfaces of the cubic cells skewed in many different angles relative to the longitudinal axes of the crystals, in one specific preferred embodiment the [111] direction of the unit cells is parallel to the longitudinal axis of the crystals 86 and corresponding longitudinal central axis 88 of the airfoil 70.

A unit cell 94 having this orientation has been illustrated schematically in Fig. 5. It should be noted that, although the unit cell 94 is of the face-centered cubic construction, only the lattice points at the corners of the unit cell 94 have been illustrated in Fig. 5, the lattice points at the center of each face being omitted for purposes of clarity of illustration. In Fig. 5, the [111] direction, parallel to the longitudinal axis of the

crystals 86 and longitudinal central axis 88 of the airfoil 70, is denoted by the arrow 106.

When the unit cell has the [111] orientation shown in Fig. 5, each of the side surfaces of the unit cell 94 extends at an acute angle relative to the longitudinal central axis 88. A line 104 extending between diagonally opposite corners of the unit cell having the [111] orientation is parallel to the axis 88. Although only a single unit cell 94 has been shown in Figs. 4 and 5, it should be understood that other unit cells of the elongated crystals 86 have the same longitudinal orientation. Within an individual crystal 86 all unit cells also share a common rotational orientation about the longitudinal central axis 88 such that the corresponding side surfaces of all unit cells are parallel. Although other crystals 86 need not share the same rotational orientation, a common longitudinal orientation of [111] exists, imparting within the airfoil 70 a common set of Young's modulus and other mechanical behavior characteristics along the longitudinal central axis 88.

The extreme cornerwise or skewed, cube diagonal, [111], orientation of the unit cell 94 provides the highest value of Young's modulus. At ambient temperature this value is approximately 44,000,000 psi versus approximately 18,000,000 psi for an [001] orientation. High creep strength has also been reported for the [111]

orientation as measured by creep rates and stress ruptur lives at elevated temperatures on tests performed using individual crystals of nickel-base superalloys. Depending on the alloy and specific test conditions of stress and temperature, the [111] orientation has been found to provide considerably less primary creep versus that of an [001] orientation and stress rupture lives that are comparable to and, in some cases, superior to those seen with an [001] orientation. Using available data for two nickel-base superalloys, one published study postulates that the [111] orientation provides the highest creep resistance and rupture lives in comparison with [001] or other orientations.

In order to form the airfoil 70 with elongated crystals or grains 86 in which the unit cells 94 are oriented with their side surfaces extending at an acute angle relative to the central axis of the crystal, the crystals 62 in the starter element 50 have unit cells which are disposed in the same orientation as the unit cells in the crystals 86 of the airfoil 70. Thus, the unit cells of each crystal 62 in the starter element 50 has a face-centered cubic construction. Each of the side surfaces of the cubic unit cells of the starter crystals 62 extends at an acute angle relative to the longitudinal axes of the crystals 62 and relative to the mold axis 66. Since the airfoil 70 is formed of elongated crystals or

grains 86 in which each of the unit cells has a [111] orientation, the longitudinally extending starter crystals 62 have unit cells which also have a [111] orientation.

During a casting operation molten metal is poured into the mold 10. The molten metal engages the upper side surface 58 of the starter element 50. The starter crystals 62 having unit cells located in the [111] orientation then nucleate airfoil crystals 86 in which the unit cells have a corresponding [111] orientation. As the crystals 86 continue to grow from the upper side surface 58 of the starter element 50 to the tip end 80 of the airfoil 70, the orientation of the unit cells 94 in the crystals 86 remains constant. Therefore, all of the unit cells in each of the airfoil crystals 86 have the same [111] orientation.

Although the starter element 50 has been shown in Fig. 3 as having been cast as one piece, it is contemplated that the starter element 50 could have a different constructions. For example, it is contemplated that the starter element 50 could be formed of a plurality of small wire-like seeds, each having the [111] unit cell orientation. These wire-like seeds can be grown or cast as single crystals in a known manner. However, it is contemplated that for production purposes, a one piece starter element may prove to be advantageous. Of course, the initial one piece starter element 50 required for

production purposes could itself be started from a starter element which is formed of a multiplicity of small wire-like seeds, each having the [111] unit cell orientation.

In view of the foregoing description, it is apparent that the present invention utilizes a directionally solidified seed or starter element 50 having elongated crystals or grains 62. The starter element or seed 50 is oriented in a mold 10 with the longitudinal axes of the crystals 62 in the starter element 50 extending parallel to the preferred direction of grain growth in the mold cavity 38. This results in the initiation or formation of elongated metal crystals or grains 86 in the mold cavity 38 at the starter element 50 with the longitudinal axes of these grains 86 extending parallel to the longitudinal axes of the elongated metal crystals 62 in the starter element.

By having the elongated crystals 62 in the seed or starter element 50 oriented with a longitudinal axis extending parallel to the direction of grain or crystal growth in the mold cavity 38, molten metal which is poured into the mold cavity comes into contact with the ends of the longitudinally extending grains or crystals 62 in the starter element. This results in the nucleation of a multiplicity of crystals or grains 86 having the same orientation as the grains or crystals 62 in the starter

element 50. The nucleation of directionally oriented crystals 86 at the starter element 50 eliminates the competitive growth zone which characterizes most prior directional solidification casting processes in which the [001] orientation is a natural outgrowth of the early stages of the solidification near the chill surface.

The longitudinally extending crystals or grains 86 which are nucleated at the ends of the grains 62 in the starter element have unit cells 94 which are disposed in the same orientation as the unit cells of the starter element. By providing a starter element 50 having elongated grains or crystals 62 with unit cells having their side surfaces skewed or extending at an acute angle to the longitudinal axes of the crystals or grains of the starter element, longitudinally extending crystals or grains 86 with unit cells having a similar orientation will be formed in the cast article. In one specific preferred embodiment it is advantageous for the unit cells in the starter element to have a [111] orientation to effect the solidification of a cast article 70 having an elongated crystal structure with the unit cells 94 having the same [111] orientation. When the unit cells 94 are oriented with all of their side surfaces extending at an acute angle relative to the longitudinal central axis of the grains of the cast product 70, the Young's modulus and creep resistance of the cast product is improved.

Although the method of the present invention can be used in casting many different types of products, the method is advantageously used to cast airfoils 70 with the elongated crystals or grains 86 having longitudinal axes extending substantially parallel to a leading edge 74 of the airfoil.

~~Having described one specific preferred embodiment of the invention, the following is claimed:~~

CLAIMS

1. A method of casting a directionally solidified article formed of elongated metal crystals having generally parallel longitudinal axes, said method comprising the steps of providing a starter element which has a plurality of elongated metal crystals with longitudinal axes which are substantially perpendicular to first and second sides of the starter element, providing a chill, providing a mold having an open end portion and a cavity in which the article is to be cast, positioning the starter element in the open end portion of the mold with the first surface of the starter element exposed to the chill and the second surface of the starter element exposed to the mold cavity, pouring molten metal into the mold cavity, and initiating the formation in the mold cavity of a plurality of elongated metal crystals having longitudinal axes extending substantially parallel to the longitudinal axes of the elongated metal crystals in the starter element, said step of initiating the formation of metal crystals in the mold cavity including the step of engaging the second side surface of the starter element with the molten metal while the first side surface of the starter element is exposed to the chill.

2. A method as set forth in claim 1 wherein said step of providing a directionally solidified starter element includes the step of providing a starter element in which the elongated metal crystals extend between the first and second sides of the starter element.

3. A method as set forth in claim 1 wherein the elongated metal crystals have longitudinally extending sides and end surfaces which extend transversely to the longitudinally extending sides and form the second side of the starter element.

4. A method as set forth in claim 1 wherein the elongated crystals in the starter element have unit cells oriented with a [111] direction in each unit cell extending substantially perpendicular to the first and second sides of the starter element.

5. A method of casting an airfoil having a longitudinal central axis, said method comprising the steps of providing a chill, providing a mold having a cavity with an airfoil molding portion having a configuration and longitudinal central axis corresponding to the configuration and longitudinal central axis of the airfoil and having a starter element receiving portion open at one end and connected at the opposite end with the

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airfoil molding portion, providing a starter element having a plurality of elongated metal crystals, positioning the starter element and mold relative to each other and to the chill with the starter element exposed to the chill and disposed in the starter element receiving portion of the mold, said step of positioning the starter element and mold relative to each other including positioning them relative to each other with the axes of the longitudinally extending crystals in the starter element extending substantially parallel to the longitudinal axis of the mold cavity, pouring molten metal into the mold cavity, engaging the starter element with the molten metal, and forming elongated metal crystals in the mold cavity with the axes of these crystals extending substantially parallel to the central axis of the mold cavity and to the axes of the elongated metal crystals in the starter element.

6. A method as set forth in claim 5 wherein the elongated crystals in the starter element have unit cells oriented with a [111] direction in each cell extending substantially parallel to the longitudinal axes of the elongated crystals in the starter element, the elongated crystals in the mold cavity having unit cells oriented with a [111] direction in each cell extending parallel to the longitudinal axes of the elongated crystals in the starter element and to the longitudinal axis of the mold cavity.

7. A method of casting a metal airfoil having a longitudinally extending leading edge portion, said method comprising the steps of providing a chill, providing a mold having a cavity at least a portion of which has a configuration corresponding to the configuration of the airfoil, providing a metal starter element having an elongated crystal structure with each elongated crystal being formed of a plurality of cubic unit cells having substantially the same orientation, positioning the mold and starter element relative to each other and to the chill with the starter element exposed to both the chill and the mold cavity and with each of the sides of the cubic unit cells in the elongated crystals extending at acute angles relative to the longitudinal axis of the portion of the mold cavity having a configuration corresponding to the leading edge of the airfoil, pouring molten metal into the mold cavity, said step of pouring molten metal into the mold cavity including the step of engaging the starter element with the molten metal, solidifying the molten metal in the mold cavity to form the airfoil, said step of solidifying the molten metal in the mold cavity including the step of solidifying the molten metal to form the leading edge portion of the airfoil with an elongated crystal structure and with each elongated crystal being formed of a plurality of cubic unit cells having substantially the same orientation in

which each of the sides of the cubic unit cells extend at an acute angle relative to the longitudinal axis of the leading edge portion of the airfoil.

8. A method as set forth in claim 7 wherein said step of solidifying the molten metal in the mold cavity to form the leading edge portion of the airfoil includes the step of solidifying the molten metal with the unit cells of the elongated crystals oriented with their [111] directions extending substantially parallel to the longitudinal axis of the leading edge portion of the airfoil.

9. A method as set forth in claim 8 wherein said step of positioning the mold and starter element relative to each other and to the chill includes positioning the starter element with the unit cells of the elongated crystals in the starter element oriented with their [111] directions extending substantially parallel to the longitudinal axis of the leading edge portion of the airfoil.

10. A method as set forth in claim 9 wherein said step of solidifying the molten metal to form the leading edge portion of the airfoil with an elongated crystal structure includes the step of initiating the formation in

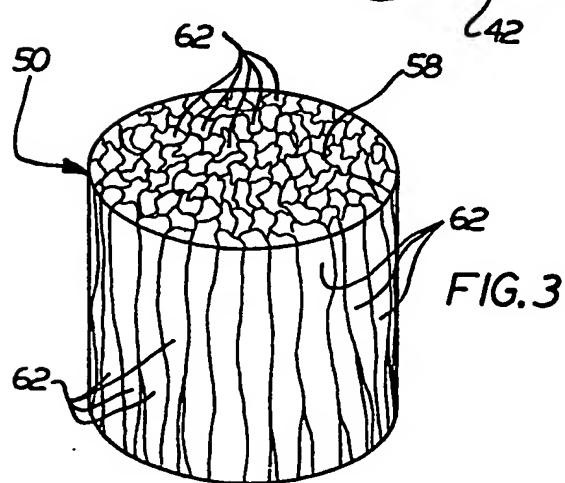
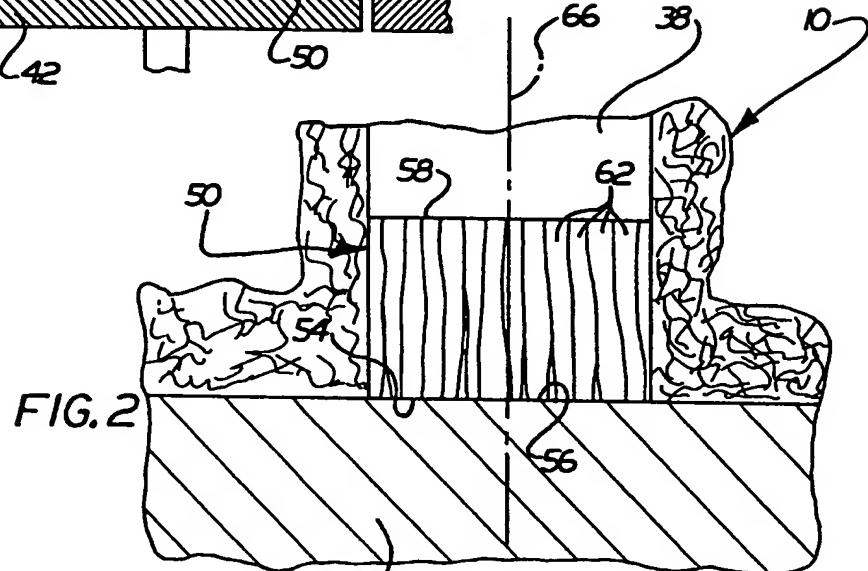
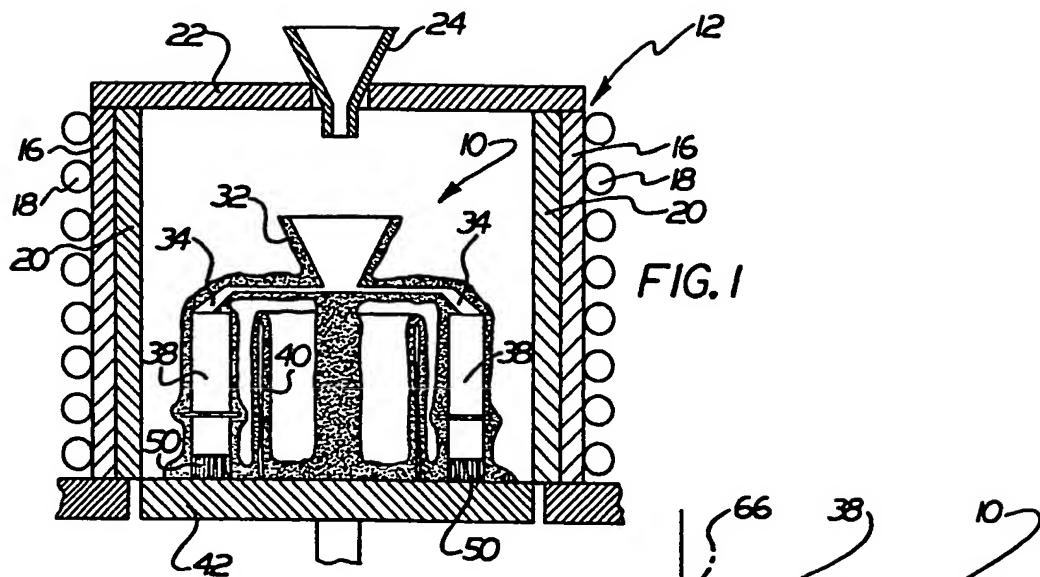
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the mold cavity of metal crystals having longitudinal axes extending substantially parallel to the longitudinal axes of the elongated crystals in the starter element and extending substantially parallel to the longitudinal axis of the portion of the mold cavity having a configuration corresponding to the leading edge of the airfoil.

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